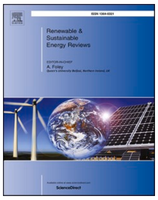
Renewable and Sustainable Energy Reviews 135 (2021) 110407

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser



Clean energy transition in Mexico: Policy recommendations for the deployment of energy storage technologies

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ARTICLE INFO

Keywords:
Energy storage
Energy policy
Energy transition
Comparative policy analysis
Energy regulation
Energy storage technologies
Mexico
Mexican policy

ABSTRACT

The adoption of a constitutional energy reform in 2013 in Mexico opened the door for private investment in the electricity sector and directed the country towards a clean energy transition. However, the expanding role of renewable energy poses new flexibility challenges for the Mexican power system. Even though energy storage technologies are one of the many solutions to add grid flexibility, they have not yet been implemented in Mexico and their consideration in new energy policies is very limited. Based on a comparative policy analysis between Mexico, the US and Germany, this paper seeks to provide policy recommendations to incentivise the deployment of energy storage technologies in Mexico. The main priority for Mexican policymakers should be to create a legal definition of energy storage and design clear market regulations. Mexico should also focus on funding demonstration projects of well-proven technologies and introducing financial incentives to accelerate investments in energy storage. Procurement targets are a key policy to create storage markets in the short term.

1. Introduction

Following the Energy Reform of 2013 and the Energy Transition Law of 2015, Mexico set a national strategy for the decarbonisation of the electricity sector and established three clean energy transition goals: 35% of the total electricity production must come from clean energy by 2024; 37.7% by 2030; and 50% by 2050 [1].[1]

The clean energy transition is now part of Mexico's international commitments to the Sustainable Development Goals and the Paris Agreement. Specifically, Mexico has vowed to substantially increase the share of renewable energy sources in its energy generation mix [2] and pledged to unconditionally lower greenhouse gases emissions by 22% of business-as-usual levels by 2030. This would imply reducing emissions from the electricity sector by 31% [3].

According to the Secretariat of Energy (SENER), the energy transition will be driven by a significant increase in variable renewable energy (VRE). SENER has predicted the installation of 26.2 GW of wind and solar PV between 2018 and 2032 and it is expected that 17% of the total electricity generation will come from these sources by 2030 [1]. This raises the question of whether the Mexican grid is flexible enough to withstand the increase in VRE.

Flexibility is the ability of a power system to react to changes in power demand and generation [4]. Traditional power systems ensure flexibility through a diverse portfolio of power plants that, taken together, can match energy demand at any time [5]. Generally, daily and seasonal demands are predicted using historical trends and, when electricity generation is insufficient, peaking power plants are deployed to meet the deficit [6]. However, the integration of VRE sources affects the stability of power systems [7] since their output can be intermittent and uncertain [8]. Thus, the higher the share of VRE in a grid, the greater the need to add flexibility [5].

One of the solutions that has emerged in the past decades is energy storage. Energy storage technologies (EST) can enhance the efficiency, reliability and security of power systems by acting as a buffer to offset the intermittency of VRE [9]. During periods of low energy demand, EST allow generation plants to operate efficiently by storing any surpluses of energy and, in periods of high demand, stored energy can be used instead of traditional fossil fuel-based peaking power plants [5]. Energy storage can thus become an essential instrument not only to ensure grid flexibility, but also to reduce the overall greenhouse emissions from the electricity sector and achieve national and international climate change mitigation commitments.

Despite their advantages, most EST have not been widely diffused in the global market. Although some EST still face high costs and technological uncertainty, it is widely accepted that the main barriers to the

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[1] According to the Electricity Industry Law, clean energy sources in Mexico include hydro, wind, solar, marine, geothermal, hydrogen, biomass, nuclear, cogeneration and other processes that meet the efficiency requirements established by the Energy Regulation Commission [39].

https://doi.org/10.1016/j.rser.2020.110407
Received 24 October 2019; Received in revised form 30 June 2020; Accepted 20 September 2020
Available online 1 October 2020
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Abbreviations

AB	Assembly Bill
ACES	Advancing Commonwealth Energy Storage
APS	Alternative Energy Portfolio Standard
CAES	Compressed Air Energy Storage
CES	Clean Energy Standard
DOE	US Department of Energy
EEG	Renewable Energy Sources Act
EEWärmeG	Renewable Energy Heat Act
EnWG	Energy Industry Act
EPIC	Electric Program Investment Charge
ERP	Energy Research Programme
ESFI	Energy Storage Funding Initiative
ESI	Energy Storage Initiative
ESR	Energy Storage Roadmap
EST	Energy Storage Technologies
FERC	Federal Energy Regulatory Commission
HB	House Bill
ISOs	Independent System Operators
KPE	Kopernikus Projects for the Energiewende
MAP	Market Incentive Programme
PHS	Pumped Hydro Storage
RD&D	Research, Development and Demonstration
REV	Reforming the Energy Vision
RPS	Renewable Portfolio Standard
RTOs	Regional Transmission Organisations
SB	Senate Bill
SENER	Secretariat of Energy (Mexico)
SGIP	Self-Generation Incentive Programme
SMART	Solar Massachusetts Renewable Target
SMES	Superconducting Magnetic Energy Storage
VRE	Variable Renewable Energy
WEM	Wholesale Electricity Market

Units

GW	Gigawatt, equivalent to one billion (10^9) watts
kW	Kilowatt, equivalent to a thousand watts
kWh	Kilowatt-hour, equivalent to a thousand watt-hours
MW	Megawatt, equivalent to one million (10^6) watts
MWh	Megawatt-hour, equivalent to one million (10^6) watt-hours

deployment of energy storage worldwide are inadequate regulatory frameworks and lack of policy support [10–12]. Thus, identifying which types of regulations and policies can successfully incentivise the deployment of EST is an essential first step for the creation and strenghtening of energy storage markets.

Previous studies have analysed several regulatory and policy landscapes and proposed solutions to expand the role of EST in electricity markets [11–15]. Nevertheless, these studies have primarily focused on developed economies, particularly in North America and Europe. Whether and how developing countries, such as Mexico, have incorporated EST into their policy agendas remains a vastly unexplored subject. In addition, the existing literature pays little attention to the timeline with which regulations and policies have been introduced in different jurisdictions and thus fails to create a clear narrative of how energy storage markets have been gradually developed over time.

This paper uses a comparative policy analysis to study the regulatory frameworks and policy strategies that have been pursued in Mexico, the US and Germany to advance the deployment of energy storage. The analysis gathers insights on how these countries have progressively eliminated barriers and incentivised investments in energy storage over the past decade. The objective of the paper is to use these insights to provide recommendations of energy storage policies that could be implemented in Mexico to support the clean energy transition.

2. Global energy storage outlook

Electricity is an energy carrier that cannot be stored per se. However, EST can convert it into a storable energy form which is then transformed back into electricity when needed [16]. EST can provide different grid services, such as peak shaving and frequency control, but there is no 'one-size-fits-all' technology that can address all needs of the power sector. The most common EST include pumped hydro storage (PHS), compressed air energy storage (CAES), flywheels, superconducting magnetic energy storage (SMES), supercapacitors, batteries and hydrogen storage [7,9,16]. Table 1 provides a detailed description of these technologies.

According to the US Department of Energy (DOE), there are now 1,355 energy storage projects in operation in the world, amounting to a total capacity of around 173.6 GW. More than 75% of this capacity is concentrated in ten countries: China, Japan, the US, Spain, Italy, India, Germany, Switzerland, France and South Korea. However, as shown in Fig. 1, most projects in operation today are located in the US [17].

Other than PHS, no EST has achieved the level of maturity necessary for widespread diffusion. In fact, 96.6% of the global storage capacity corresponds to PHS [17]. However, battery storage has gained traction in the past decade, mainly due to significant cost reductions of Lithium-ion batteries [18]. Battery storage now makes up 1% of the global storage capacity (1.7 GW) [17].

3. Evolution of the electricity sector in Mexico

Before 2013, the electricity sector in Mexico had historically consisted of a monopolistic market controlled by the Federal Electricity Commission. However, the Energy Reform of 2013 opened the door for private parties to participate in the electricity market through a constitutional amendment. Today, the State maintains exclusive control of all transmission and distribution activities, but private investment is possible in two ways: directly, for electricity generation and commercialization activities, which are now operating under a regime of free competition; and indirectly, through contracts with the government for maintenance, management, operation or expansion activities required for transmission and distribution [19].

In 2017, Mexico had a total installed capacity of 75.68 GW, 70.5% of which corresponded to conventional energy and only 29.5% to clean energy [1]. While fossil fuels are still dominant, clean energy sources have increasingly been gaining ground since the Energy Reform, and government forecasts indicate that the electricity sector will continue to focus on clean energy in the following decade. Specifically, SENER has projected the installation of 66.91 GW between 2018 and 2032, 55% of which will be clean energy technologies [1].

Within the category of clean energy, renewable energy sources are expected to experience the largest increase in capacity, with an annual average growth rate of 6.1% until 2032. Wind and solar PV are predicted to increase the most, with annual growth rates of 10.2% and 13.5%, respectively [20].

Fig. 2 presents the evolution of clean energy capacity in Mexico between 2007 and 2017, as well as the official forecasts for the period between 2018 and 2032. This shows that the following decade is expected to be a breakthrough for renewable energy in the country, particularly for wind and solar PV.

Table 1
Summary of EST.

Technology	Mechanism	Status	Type	Scale	Services *	Efficiency
PHS	*Charge:* electricity is used to pump water from a lower reservoir to an upper reservoir. *Discharge:* water flows out of the upper reservoir and activates turbines that generate electricity.	Mature	Mechanical	Large scale Long-term	Seasonal shifting, peak shaving, load levelling	70–85%
CAES	*Charge:* electricity is used to compress air into a storage vessel (underground caverns or tanks). *Discharge:* air is released, heated, and expanded in a turbine to produce electricity.	Developed	Mechanical	Large scale Long-term	Seasonal shifting, peak shaving, load levelling	40–70%
Flywheel	*Charge:* an electric motor accelerates the flywheel, which keeps rotating until discharged. *Discharge:* the flywheel slows down, and energy is transferred through electromagnetic induction to a generator to produce electricity.	Commercialised	Mechanical	Small scale Short-term	Power quality, black star	70–95%
SMES	*Charge:* electricity is transformed into a DC current that is induced into a coil of superconductive materials of nearly zero resistance operating under cryogenic conditions. The induced current creates a magnetic field. *Discharge:* stored energy is released to the grid by discharging the coil and transforming the current back to AC.	Demonstration	Electrical	Small scale Short-term	Power quality, black start, spinning reserve	85–99%
Supercapacitors	*Charge:* electricity is stored in the form of an electric field between two electrodes caused by a voltage differential. *Discharge:* voltage drops and releases electricity back to the grid.	Demonstration	Electrical	Small scale Short-term	Power quality, black start, spinning reserve	90–95%
Batteries	*Charge:* electricity is stored in the form of chemical energy. *Discharge:* electricity is produced through electrochemical reactions.	Demonstration, commercialised, mature (depending on technology)	Electrochemical	Small scale Short- to long-term	Spinning reserve, peak shaving, frequency regulation, black start, power quality	60–95% (depending on technology)
Hydrogen	*Charge:* electricity is used to produce hydrogen through electrolysis. Hydrogen is stored either as pressured gas, cold liquid or in adsorbing or absorbing materials. *Discharge:* Hydrogen is supplied to a fuel cell, which produces electricity and water.	Demonstration	Electrochemical	Small scale Short-term	Standing reserve, black start	25–45%

Sources [5–7,16,18]: * Non-exhaustive list

4. Methodology

4.1. Comparative policy analysis

A comparative policy analysis between Mexico, the US and Germany was used to study the development of energy storage regulations and policies. These jurisdictions were selected based on three criteria. First, all jurisdictions must operate within wholesale electricity markets (WEM), so that regulations and policies designed outside of competitive markets are excluded. Second, all jurisdictions must have implemented policies specifically directed at energy storage. This is important to distinguish targeted policies from other instruments that might have an impact on energy storage but are not aimed at incentivising its deployment. For example, renewable energy portfolios can indirectly increase the demand for storage, but they are not necessarily designed for this purpose. Finally, the compared jurisdictions must differ from Mexico in terms of energy storage deployment outcomes.

The US and Germany comply with all the criteria, as they operate within WEM, they have implemented several energy storage policies, and have become global leaders in energy storage. While Mexico and Germany were analysed at the national level, the US was also studied at the state level because its WEM are organized regionally. California, Massachusetts and New York were selected because they are the only states operating within WEM that have also enacted specific energy storage mandates.

The comparative policy analysis was based on a review of relevant literature about the contextual differences between the jurisdictions, regulatory barriers, and favourable regulations and policies for the deployment of energy storage. The results were organized according to three key elements:

i. **Context:** broad energy policy context, including the current state of energy storage deployment, VRE integration and future energy transition goals.
ii. **Regulatory framework:** regulations regarding the participation and operation of energy storage in electricity markets.
iii. **Energy storage policy:** technology-push and market-pull instruments directed at energy storage.

4.2. Literature search, selection and analysis

The literature used for the comparative policy analysis comprised

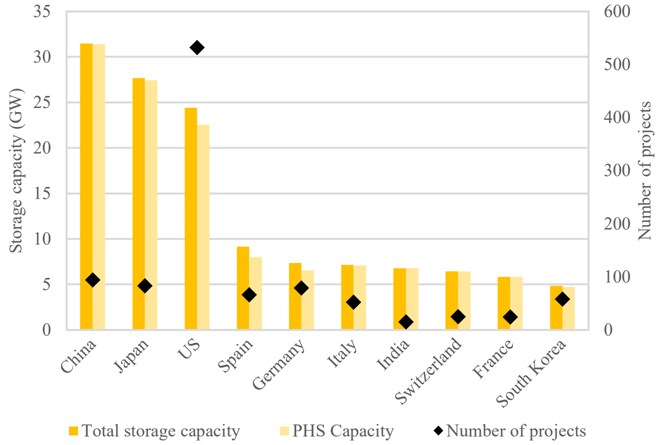

Fig. 1. Main global actors in energy storage in 2019. The bars show the total operational storage capacity in dark yellow and the PHS capacity in light yellow (left axis). The black diamonds show the number of active storage projects (right axis). Data from Ref. [17]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

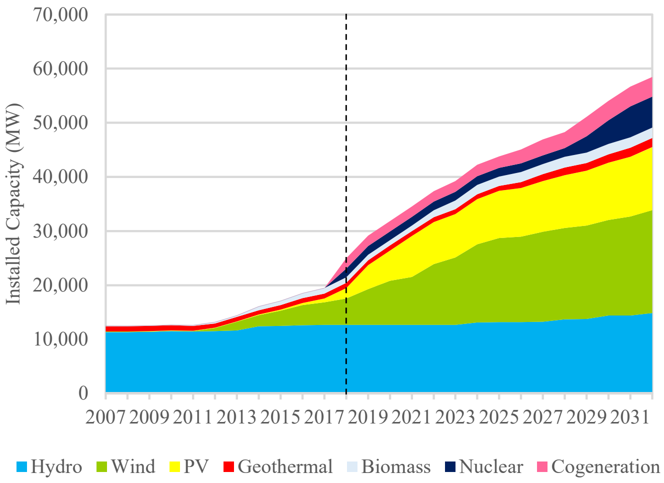

Fig. 2. Evolution and forecast of clean energy capacity in Mexico 2007–2032. The dotted line separates real data from the future energy forecast. Data from Ref. [1,20].

both primary sources, including legal documents, policy reviews and reports published by governments, and secondary literature from peer-reviewed journals. These sources were obtained, selected, and analysed following the methodology presented in Fig. 3. First, all potential sources were collected using a Boolean search. Second, all titles and abstracts were scanned to determine the sources' relevance to the three key elements of the analysis. Then, the pre-selected sources were reviewed in full and filtered according to specific selection criteria. Finally, the selected literature was analysed to contrast the regulatory and policy strategies among all jurisdictions, gather policy-relevant lessons from the US and Germany, and outline a series of recommendations for Mexico.

The results of the literature search were complemented with data from energy databases and reports from national and international authorities, including SENER, DOE, the US Energy Information Administration, the Germany Federal Ministry for Economic Affairs and Energy, and the International Energy Agency.

5. Results

5.1. Contextual differences between Mexico, the US and Germany

Mexico, the US, and Germany have significant differences in terms of energy storage deployment, the degree of penetration of VRE in their energy generation mix, and their general energy policy agenda.

In Mexico, energy storage has been scarcely deployed in small-scale applications [21] and the only official figure reported to date indicates that there were less than 5 MW of storage in 2016 [22]. In contrast, the US has deployed 24.4 GW, the third largest storage capacity in the world [17]. California leads all states with 4.2 GW, followed by Massachusetts with 1.7 GW, and New York with 1.4 GW. Meanwhile, Germany has 6.7 GW of storage, the fifth largest capacity in the world [17].

Fig. 4 presents the combined utility-scale and behind-the-meter storage deployments in the US and Germany between 2013 and 2018. In this period, the US and Germany increased their storage capacities by 1,138 MW and 763 MW, respectively. In both countries, the largest capacity additions occurred between 2017 and 2018 [23].

As shown in Fig. 5, Germany has the highest share of VRE. In 2018, more than 24% of the electricity produced in Germany came from solar and wind energy. Mexico and the US only reached a share of 4.4.% and 8.3%, respectively [24]. While the integration of wind and solar energy has been slow in the US at the federal level, VRE generation increased more than 2.5 times in California over the past six years and reached 21% by 2018.

Fig. 6 presents different energy transition goals in all jurisdictions for the first half of the century. Mexico has the least ambitious goals, as they refer to "clean energy"[1], instead of renewable or carbon-free electricity, and they plan for a slower integration of VRE. For example, while Mexico aims to reach 50% clean energy generation by 2050, California expects to reach 60% renewable energy by 2030.

There is no national energy transition strategy in the US, but all states under analysis have created their own agendas. In 2002, California started a Renewable Portfolio Standard (RPS) programme with a procurement target of 20% renewable energy by 2017 [26]. In 2018, the RPS increased to 60% by 2030 and a new 100% zero-carbon electricity goal was established for 2045 [27].

Since 2009, Massachusetts is operating four energy portfolio standards: RPS Class I, RPS Class II Renewable, RPS Class II Waste-to-Energy, and the Alternative Energy Portfolio Standard (APS). In particular, RPS Class I, which mandates retail electricity suppliers to obtain a percentage of their electricity from renewable sources, will lead Massachusetts to reach 35% renewable energy generation by 2030 [28]. In 2017, a Clean Energy Standard (CES) was introduced requiring retail suppliers to obtain a minimum percentage of their electricity sales from clean energy sources,[2] in addition to their obligations to the RPS Class I. With this, clean energy generation is expected to increase to 80% by 2050 [29].

New York adopted the Reforming the Energy Vision (REV) initiative in 2015 and created a CES to reach 50% renewable energy generation by 2030 [30,31]. With the enactment of the Climate Leadership and Community Protection Act of 2019, New York committed to reach 70% renewable energy by 2030, as well as 100% carbon-free electricity by 2040 [32].

Meanwhile, Germany has adopted a national, multi-sectorial energy transition strategy known as the Energiewende. The Energy Concept document, a long-term policy guideline published in 2010, set a target to increase the share of renewable energy to 35% of the gross electricity consumption by 2020 [33]. This was legislated into the Renewable

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[2] In Massachusetts, clean energy includes renewable sources and all generation units whose net life-cycle greenhouse emissions are at least 50% less than those produced by a new combined-cycle natural gas plant over a 20-year life cycle [106].

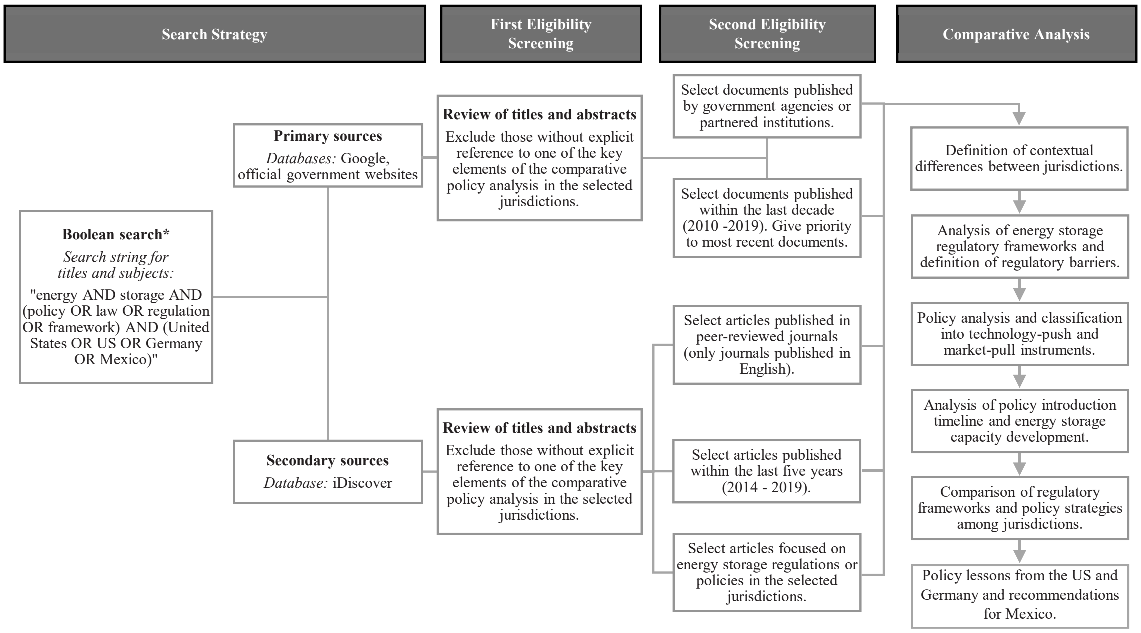
Search Strategy
First Eligibility Screening
Second Eligibility Screening
Comparative Analysis
Boolean search*
Search string for titles and subjects:
"energy AND storage AND (policy OR law OR regulation OR framework) AND (United States OR US OR Germany OR Mexico)"
Primary sources
Databases: Google, official government websites
Secondary sources
Database: iDiscover
Review of titles and abstracts
Exclude those without explicit reference to one of the key elements of the comparative policy analysis in the selected jurisdictions.
Review of titles and abstracts
Exclude those without explicit reference to one of the key elements of the comparative policy analysis in the selected jurisdictions.
Select documents published by government agencies or partnered institutions.
Select documents published within the last decade (2010 -2019). Give priority to most recent documents.
Select articles published in peer-reviewed journals (only journals published in English).
Select articles published within the last five years (2014 - 2019).
Select articles focused on energy storage regulations or policies in the selected jurisdictions.
Definition of contextual differences between jurisdictions.
Analysis of energy storage regulatory frameworks and definition of regulatory barriers.
Policy analysis and classification into technology-push and market-pull instruments.
Analysis of policy introduction timeline and energy storage capacity development.
Comparison of regulatory frameworks and policy strategies among jurisdictions.
Policy lessons from the US and Germany and recommendations for Mexico.

Fig. 3. Methodology for literature search, selection and analysis. The methodology included a literature search strategy with Boolean operators, a two-step screening process for literature selection, and a comparative analysis of the results. * This search was also conducted in Spanish for Mexican primary sources.

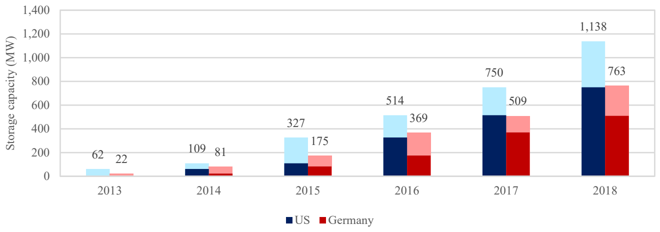

Fig. 4. Deployment of energy storage capacity the US and Germany 2013–2018. The light shading represents the new annual storage capacity additions. Data from Ref. [23].

Energy Sources Act (EEG) in 2012 [34], but suffered several amendments during the last decade. The latest version, EEG 2017, established the targets of 40–45% renewable energy consumption by 2025, 55–60% by 2035 and at least 80% by 2050 [35]. However, the new federal government has adopted a Coalition Agreement that provides for an increased goal of 65% renewable energy consumption by 2030 [36].

In addition to the increase in renewable energy, Germany is planning two other major transformations of the electricity sector: the complete phase-out of nuclear power by 2022, established by the 13th Act Amending the Atomic Energy Act, and the complete phase-out of coal power by 2038, which is now in the process of being legislated [37].

5.2. *Energy storage regulatory frameworks*

5.2.1. *Mexico*

Energy storage appears scarcely in Mexican legislation and the few regulations that mention it leave the door open to potentially consider EST as either generation assets or transmission and distribution assets [19]. If EST were regulated as generation assets, they could operate under a regime of free competition. On the other hand, transmission and distribution activities can only be conducted by the State or contracted private parties acting on behalf of the government.

Under the Basis of the Electricity Market, a federal regulation of the WEM, EST must be registered as generation plants to commercialise electricity and other products in the WEM [38]. This could be considered a consequence of the Electricity Industry Law of 2014, which defines generation plants as those facilities that produce electricity or associated products, i.e. products required for the quality, reliability, continuity, security and sustainability of the power system [39]. Even though energy storage is not explicitly mentioned in this definition, an argument could be made to consider EST as generation plants under federal law [19]. Nevertheless, the Energy Transition Law of 2015 also links energy storage to transmission and distribution activities by including EST in SENER's Smart Grids Programme [19,40].

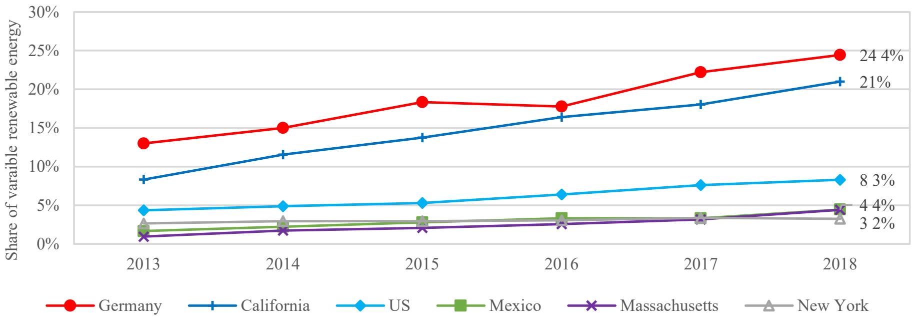

Fig. 5. Evolution of VRE in Mexico, the US and Germany 2013–2018. The share of VRE is the percentage of the total energy generation in a country or state that was produced by solar and wind energy sources. Data from Ref. [24,25].

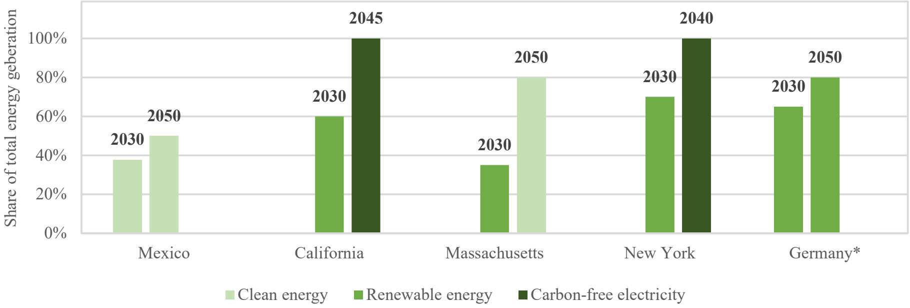

Fig. 6. Energy transition goals in Mexico, the US and Germany. Energy goals are divided into three categories: clean energy (see footnotes 1 and 2) in light green, renewable energy in green, and carbon-free electricity in dark green. * Germany's goals refer to energy consumption, instead of generation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

There are no other rules regarding the participation of energy storage in the WEM and as of 2018, no registration requests for energy storage units had been made [19], so there is also no evidence of how EST could operate in the WEM.

5.2.2. US

The US electricity sector is governed by complex market regulations that change significantly across the country. Lacking a comprehensive national regulatory framework, each state has opted for different market structures, from vertically-integrated utility models to competitive WEM [41]. WEM are operated by Independent System Operators (ISOs) and Regional Transmission Organisations (RTOs), which have the authority to develop their own regulations, as long as they comply with the overarching rulings of the Federal Energy Regulatory Commission (FERC) [12].

In 2015, FERC initiated a process to study the barriers that limit the participation of EST in the WEM and concluded that ISO/RTOs rules were "unjust and unreasonable" in three main areas: access to market participation, competition, and just and reasonable rates. This triggered FERC to release Order 841 in 2018, requiring all ISO/RTOs to evaluate their tariffs and establish participation models that ensure that EST are able to offer all services they are technically capable of providing in the WEM, set the wholesale clearing price as both wholesale sellers and buyers, and resell electricity at the wholesale locational marginal price. Participation models must also include bidding parameters that account for the physical and operational characteristics of EST and establish minimum size requirements for market participation that do not exceed 100 kW [42]. Through this ruling, EST are granted open access to the market, a competitive playing field, and fair compensation for the services they provide.

FERC's Order 841, often referred as a landmark of energy storage rulemaking [43,44], has built on at least eight previous rulings that partially addressed market barriers to energy storage [12]. Table 2 presents all FERC regulations related to energy storage issued between 2007 and 2018 and their main regulatory objectives.

5.2.3. Germany

In 2016, Germany adopted the Act on the Further Development of the Electricity Market and began a gradual regulatory reform to (i) adapt the WEM to the increasing shares of VRE and (ii) establish rules for the operation of energy storage and other flexibility resources [37,53]. Particularly, the Energy Industry Act (EnWG) and the EEG have been amended to address market distortions against the operation of EST.

The EnWG now includes supply and demand flexibility as one of the main principles of the German electricity market and provides explicit benefits to EST. New storage facilities might, under certain circumstances, be exempted from grid access charges for 20 years (§118, para. 6). The exemption only applies to electricity that is withdrawn from and

Table 2
FERC regulations affecting energy storage and main regulatory objectives.

Order	Date	Title	Description	Improve pricing practices	Expand market access	Ref.
841	02/18	Electric Storage Participation in Markets Operated by RTOs and ISOs	Removes barriers to the participation of electric storage resources in capacity, energy and ancillary services markets.	X	X	[42]
825	06/16	Settlement Intervals and Shortage Pricing in Markets Operated by RTOs and ISOs	Reforms pricing practices to compensate resources according to the value of their services in real-time markets.	X		[45]
784	07/13	Third-Party Provision of Ancillary Services; Accounting and Financial Reporting for New Electric Storage Technologies	Orders public utility transmission providers to consider speed and accuracy of regulation resources and improve accounting and reporting requirements for energy storage.	X		[46]
764	06/12	Integration of Variable Energy Resources	Removes barriers for the integration of variable energy sources through intra-hourly scheduling requirements.	X	X	[47]
755	10/11	Frequency Regulation Compensation in Organized Wholesale Power Markets	Applies a two-tier payment for ancillary services of frequency regulation that considers both capacity and performance.	X		[48]
1000	07/11	Transmission Planning and Cost Allocation by Transmission Owning and Operating Public Utilities	Provides for regional and inter-regional cost allocation methods for new transmission facilities.	X		[49]
745	03/11	Demand Response Compensation in Organized Wholesale Energy Markets	Provides for the participation of demand response resources and compensation based on the locational marginal price.	X	X	[50]
719	10/08	Wholesale Competition in Regions with Organized Electric Markets	Amends the Federal Power Act to improve the operation of demand response resources and market pricing.	X		[51]
890	02/07	Preventing Undue Discrimination and Preference in Transmission Service	Orders ISO/RTOs to consider intermittent generators in ancillary services markets and alter tariffs to remunerate them.	X	X	[52]

re-injected into the same transmission or distribution network [54]. However, this condition is waived for power-to-gas installations that produce hydrogen or biogas and instead, these facilities are exempted from both grid access charges and gas injection fees [54,55].

Since the enactment of the EEG in 2000, a levy known as the EEG-surcharge was introduced for every kWh of electricity consumption to finance subsidies for renewable energy [37]. In the absence of a legal definition of energy storage, EST have so far been considered both electricity consumers and generators. Stored energy is, in principle, subject to a double EEG-surcharge: once when electricity is "consumed" for storage and once when electricity is "generated" again, released back into the grid, and finally consumed by an end-user [11]. To alleviate this burden, the EEG 2017 established that electricity "consumed" for storage is exempted from the EEG-surcharge as long as a payment is done for the electricity "generated" by the storage unit and consumed by an end-user (§61 l, para 1). Storage losses are also exempted from the levy [35].

Additionally, §61a and §61b of the EEG include exemptions that impact EST used for self-supply, i.e. stored electricity that is not fed into the grid but consumed by the generator. Under these rulings, a facility of less than 10 kW, such as a residential solar-plus-storage installation, is exempted from the EEG-surcharge for up to 10 MWh per year [35]. Larger facilities are not exempted, but are only required to pay 40% of the levy [35,56].

Another potential benefit is provided by the Electricity Tax Act, which exempts electricity used for electricity generation from being taxed (§9, para. 1, no. 2) [57]. The Electricity Tax Ordinance specifies that this exemption is applicable for PHS (§12, para. 2), but it does not mention any other type of EST explicitly [58]. However, some argue this exemption could potentially be extended to other EST by analogy [55].

5.3. Energy storage policies

5.3.1. Mexico

Energy storage was first included as part of Mexico's long-term policies in the Transition Strategy to Promote the Use of Cleaner Technologies and Fuels published by SENER in 2016. In particular, the strategy specified nine action lines for energy storage (see Table 3) and defined EST as a "key element" to support the future integration of VRE in the country [22].

SENER created a working group on energy storage to analyse the development status of EST and evaluate their potential role in Mexico. In 2018, this group published a list of national priorities and proposed an energy storage roadmap (ESR) from 2018 to 2022. The roadmap suggests developing regulations and promoting research, development and demonstration (RD&D) projects [59], but these proposals have not yet been adopted as a formal policy guideline.

Table 3
Action lines for energy storage in Mexico.

Category	Action line
Regulation	• Create regulations for the interconnection of EST. • Define the role of ancillary services provided by EST. • Create rules for the construction, operation and retirement of EST.
Institutions	• Develop a roadmap to identify objectives, needs, challenges and priorities for the deployment of EST. • Publish information about the WEM to facilitate the modelling of EST.
Capacity building	• Integrate EST into the Strategic Training Programme for Human Resources in Energy Matters.
Markets and finance	• Promote the development of business models to incentivise technologies, products and services in the energy storage value chain.
RD&D and innovation	• Promote funding for research projects, technological development and innovation. • Promote national and international collaboration in research, development and innovation in energy storage.

Nevertheless, Mexico is expected to start energy storage RD&D projects in the next years. For instance, under the Smart Grids Programme, a research programme for storage technologies that provide black start services must be developed by 2022, as well as demonstration projects for batteries, flywheels and CAES by 2024 [60]. In 2019, a new research project in collaboration with the University of Birmingham was also announced to study the potential of using EST in rural communities in Mexico [61].

5.3.2. US

The US has implemented several technology-push and market-pull policies for energy storage at the federal and state level.

DOE is at the centre of most federal efforts, mainly in the form of RD&D funding, loans, and knowledge diffusion policies.[3] After the enactment of the American Recovery and Reinvestment Act of 2009, DOE provided $185 million for storage demonstration projects. This investment resulted in the addition of almost 538 MW of storage capacity [62]. In 2018, DOE committed an additional $30 million to the Duration Addition to electricitY Storage (DAYS) programme, which aims to develop long-term storage technologies [18]. DOE's Loan Programs Office has also financed several innovative projects, including thermal energy storage in concentrating solar power plants and advanced battery systems for transportation [63]. Moreover, DOE runs the Global Energy Storage Database, an online database of research-grade information about energy storage projects, policies, factsheets, and latest scientific advances [17].

Privately-owned battery storage systems are also eligible for two federal tax incentives. Under the Modified Accelerated Cost Recovery System, the current tax depreciation system in the US, standalone and solar-plus-storage systems can receive seven to five-year depreciation schedules, equivalent to up to a 21% reduction in capital costs. Solar-plus-storage systems can also obtain investment tax credits of up to 30% [64].

California has become the front-runner in the development of energy storage policies in the US [65]. This state has provided funding for more than thirty RD&D projects through the Electric Program Investment Charge (EPIC) programme [66] and has become a pioneer in testing and deploying large-scale Lithium-ion battery storage [65]. California has also been home to foundational demonstration projects that proved the value of batteries for frequency regulation and enhancing the reliability of microgrids [66].

In 2010, California enacted Assembly Bill (AB) 2514 and became the first state in the US to mandate utilities to procure 1.3 GW of storage capacity by 2020 [67]. This procurement target was complemented by AB 2868, which added an extra 500 MW target [68]; Senate Bill (SB) 801, which required private utilities in the Los Angeles basin to deploy at least 20 MW of storage [69]; and SB 1369, which added green electrolytic hydrogen as one of the eligible technologies to be targeted for increase [70]. As of August 2018, almost 1.5 GW had been procured or were seeking approval in California due to these rulings [66].

California also published an ESR detailing actions to expand revenue opportunities and reduce storage costs [71], and has promoted energy storage through different renewable mandates. For example, SB 350 and SB 100 established storage as a means to achieve the goals of the RPS [27,72]; SB 338 required utilities to rely on energy storage and other strategies to meet peak electricity needs [73]; and AB 33 required the state to analyse the potential of long-term storage to support VRE integration [74].

For over a decade, hybrid and standalone storage systems in California have been eligible to receive rebates for behind-the-meter applications through the Self-Generation Incentive Programme (SGIP) [66].

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[3] Knowledge diffusion policies are those directed at increasing the supply of knowledge for education and capacity-building purposes.

The programme was expanded in 2016, when AB 1637 allocated $249 million for small-scale storage [75], and in 2018, when SB 700 added roughly $830 million for behind-the-meter storage [65,76].

Massachusetts launched the Energy Storage Initiative (ESI) in 2015 as a strategy to advance EST through research, demonstrations projects, procurement targets and other policies. This initiative has positioned Massachusetts as one of the leaders in energy storage policies in the US [77]. As part of the ESI, Massachusetts published an ESR in 2016 [78] and enacted House Bill (HB) 4568, which called for the creation of an energy storage procurement target [79]. The state's initial goal was 200 MWh by 2020 [80], but it was further expanded to 1000 MWh by 2025 (HB 4857) [81].

Massachusetts also created the Solar Massachusetts Renewable Target (SMART) programme, the first in the US to offer incentives specifically to solar-plus-storage projects, and the Advancing Commonwealth Energy Storage (ACES) programme, which has awarded around $20 million in grants to 26 storage projects. By 2019, the SMART interconnection queue reached more than 130 MW and ACES projects amounted to 32 MW and 85 MWh of storage [77,80]. The state is also developing a Clean Peak Energy Standard to provide additional incentives for clean technologies that could reduce demand during seasonal peak demand periods [80].

An interesting feature of Massachusetts' policy is that flywheel storage has been part of the APS procurement obligations since 2009. Fuel cells, which could potentially include hydrogen storage, were also introduced to the APS in 2017 [28].

New York has announced the most ambitious storage procurement target yet [82]. Through the landmark Order 18-E−0130, New York set a target of 3,000 MW of storage by 2030, with an interim goal of 1,500 MW by 2025 [83], and authorized $350 million in bridge incentives to support solar-plus-storage, retail and bulk storage facilities. New York also released an ESR, started offering free expert-driven technical assistance to energy storage vendors, and opened new financing opportunities through the New York Green Bank [84]. By the end of 2019, 706 MW had been deployed or contracted because of these measures [85].

New York's energy storage policies are part of the broader efforts that started with the REV initiative in 2015. Through REV, New York has been able to complete seven storage demonstration projects and create public-private partnerships to support the commercialization of EST [30,86]. Similar to Massachusetts, New York also includes fuel cells as an eligible technology under its CES [31].

Figs. 7–9 present a timeline of the introduction of energy storage policies in California, Massachusetts and New York, along with the evolution of the operational storage capacity in each state between 2008 and 2018.

5.3.3. Germany

Recognising the potential role of energy storage in the Energiewende, Germany has implemented several technology-push and market-pull policies, with an emphasis on RD&D.

Under the 6th Energy Research Programme (ERP), Germany created the Energy Storage Funding Initiative (ESFI), which awarded €200 million for around 250 energy storage projects between 2012 and 2018 [88,89]. The federal government also committed €120 million for the Kopernikus Projects for the Energiewende (KPE) initiative, which provides funding for four core research projects related to different aspects of energy storage, including Power-to-X technologies (P2X), flexible grid structures (ENSURE), flexible industrial processes (SynEnergie) and the interaction among different sectors in the energy system (ENavi) [37,90].

Germany is now under the 7th ERP, which plans to provide €6.4 billion for energy-related RD&D until 2022. The focus areas of the programme include EST in general, as well as specific technologies, such as batteries, fuel cells and thermal storage [91]. The programme also introduced living labs as a new funding format to test technologies that are close to market-ready. The first call for living labs targeted hydrogen technologies, large-scale energy storage, and energy-efficient city quarters [37,92]. Moreover, Germany has created EnArgus, an online database of energy-related RD&D projects [37,93], as well as a website about storage projects funded through the ESFI [94].

In 2018, Germany spent over €45 million in energy storage RD&D. Over half of the budget was directed at electrochemical storage, including innovative technologies, such as redox-flow and post-lithium batteries. Germany also spent more than €24 million in hydrogen and fuel cell research, including €2 million specifically directed at hydrogen storage. Devoting large resources to electrochemical storage and hydrogen technologies is a trend that has been present in Germany since 2012 [94].

Germany was the first electricity market to introduce incentives directly targeting residential solar-plus-storage systems [14]. In 2013, the state-owned bank KfW launched programme 275, which offered low-interest loans and investment grants for 30% of the capital costs of solar-plus-storage installations until 2016. In that period, KfW invested around €60 million in almost 19,000 of these projects. In 2016, the programme was reformed and relaunched with €30 million until 2018 [88,95].

Since 2009, KfW offers financing options for battery and Power-to-X storage systems (programme 270) [96], as well as large-scale heat storage projects (programme 271/281) [97]. Small-scale heat storage units can obtain subsidies through the Market Incentive Programme (MAP), which provides grants for renewable heating and cooling installations [98]. MAP was created in 1999, but the relevance of the programme and heat storage itself was boosted by the Renewable Energy Heat Act (EEWärmeG) of 2009, which outlined a plan to increase the share of renewable energy in heating [37,98].

Although Germany has not adopted a specific ESR, a plan for expanding the country's storage capacity was included in the Energy

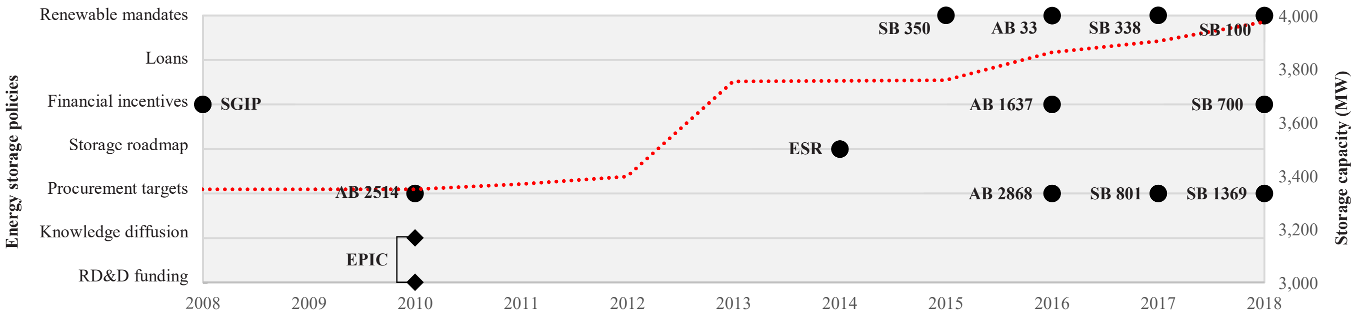

Fig. 7. Introduction of energy storage policies and operational storage capacity in California. Technology-push policies are marked as diamonds and market-pull policies are marked as circles (left axis). The dotted line represents the operational storage capacity in MW (right axis), according to Ref. [87].

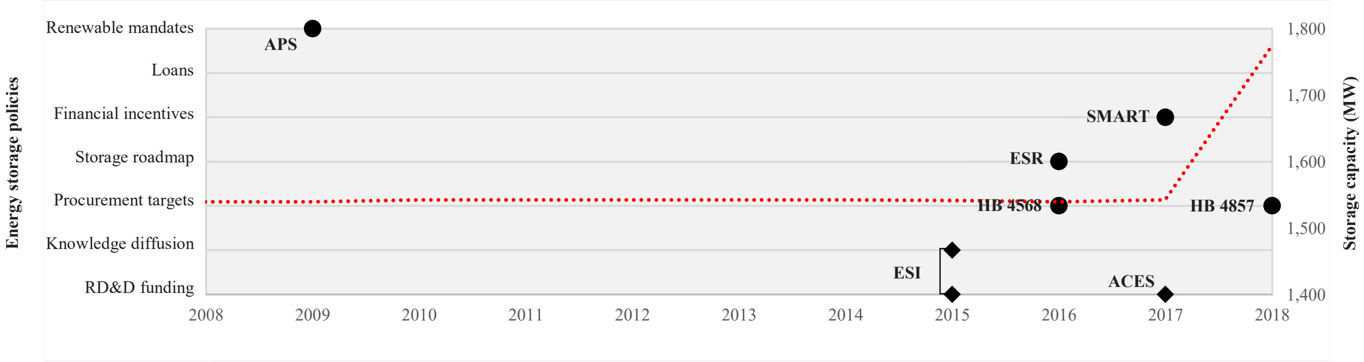

Fig. 8. Introduction of energy storage policies and operational storage capacity in Massachusetts. Technology-push policies are marked as diamonds and market-pull policies are marked as circles (left axis). The dotted line represents the operational storage capacity in MW (right axis), according to Ref. [87].

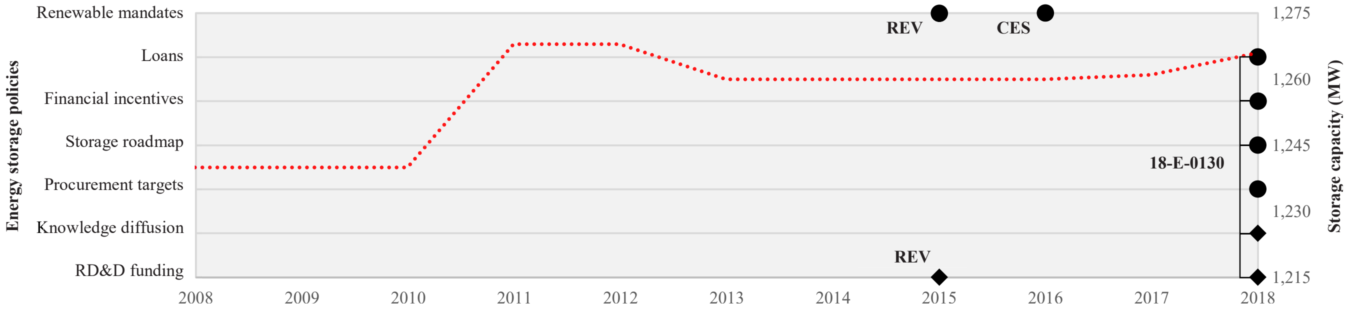

Fig. 9. Introduction of energy storage policies and operational storage capacity in New York. Technology-push policies are marked as diamonds and market-pull policies are marked as circles (left axis). The dotted line represents the operational storage capacity in MW (right axis), according to Ref. [87].

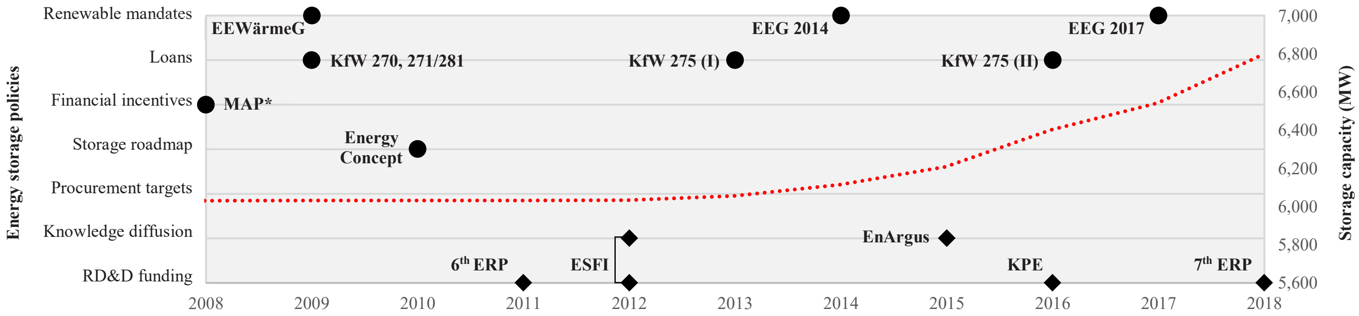

Fig. 10. Introduction of energy storage policies and operational storage capacity in Germany. Technology-push policies are marked as diamonds and market-pull policies are marked as circles (left axis). The dotted line represents the operational storage capacity in MW (right axis), according to Ref. [23] (2013–2018) and [17] (2008–2012). * The MAP programme exists since 1999.

Concept document of 2010 [33], and, as explained in Section 5.2.3, renewable mandates in Germany have been reshaped to support the deployment of energy storage.

In its new Coalition Agreement, the German government committed to promote investments in energy storage to ensure electricity supply security and reduce EEG costs. The government committed to continue RD&D funding for energy storage, to support heat storage, and to enable storage facilities to provide several services simultaneously. The Coalition Agreement also set the goals of becoming leaders in battery storage production and strengthening hydrogen technologies in Germany [36].

The 7th ERP and the Coalition Agreement indicate that energy storage will remain an important research priority in Germany in the following years.

Fig. 10 presents a timeline of the introduction of energy storage policies in Germany and the evolution of its operational storage capacity, between 2008 and 2018.

6. Discussion

6.1. Lessons from the US and Germany

The first lesson learned from the US and Germany is the relevance of broader energy policy agendas to the deployment of energy storage. Energy transition goals are particularly important for two reasons. First, from a technical perspective, the storage capacity that a country would require depends on the extent to which VRE sources are integrated into the grid, i.e. energy storage might not be necessary until the share of VRE exceeds certain threshold [8,99–103]. Second, the growth of VRE can be fostered or limited by the storage capacity of a power system. For example, EST can increase the profitability of wind and solar PV by avoiding curtailment [102] or by increasing self-consumption [56]. Therefore, it can be expected that stronger energy storage policies will be developed in jurisdictions that anticipate a strong penetration of VRE [11].

Indeed, energy storage policies have been created alongside broader decarbonisation strategies, such as California's and Massachusetts' RPS, New York's REV and Germany's Energiewende [66,78,80,83], and policymakers in these jurisdictions have framed EST as a means to achieve ambitious energy transition goals.

The largest growth of storage capacity has taken place in California and Germany (see Figs. 7 and 10), where the shares of VRE are the highest today (see Fig. 5). However, even in these jurisdictions, a transition to widespread diffusion has not occurred. This supports the prevailing argument in the literature that energy storage deployment is still contingent on the creation of strong regulations and policies that eliminate barriers, guarantee revenue streams and provide profit opportunities for EST [10–13].

Traditional regulatory frameworks were found to be a key barrier to the deployment of energy storage in all jurisdictions. In the US, WEM included complex technical rules and bidding parameters that favoured traditional technologies and limited revenue streams for energy storage. EST were often not eligible to participate in markets due to technical restriction rules, they were not allowed to simultaneously offer different services, or there were simply no existing markets for many of their services [11,13]. In Germany, the lack of a legal definition of energy storage imposes extra burdens on EST, particularly under the EEG. Investments in storage, specifically PHS, have been deferred in Germany because their operation is not cost-effective under the current electricity pricing framework [56].

The US and Germany have addressed regulatory barriers differently. The US followed a systematic reforming process of federal regulations that culminated in FERC's Order 841, a ruling that has been praised for finally creating a "clear regulatory framework" [44] and signalling that energy storage is no longer a "player on the sidelines" [12]. Meanwhile, Germany has alleviated certain burdens by adding exemptions for energy storage in existing federal laws. However, these exemptions apply under conditions that must be revised on a case-by-case basis, and more transformative regulations to reform market rules in favour of EST are still lacking. This framework might not be enough to move energy storage towards widespread diffusion in the short-term.

The US and Germany have also developed different policy strategies to support energy storage. At the federal level, the US has focused on providing funding for RD&D and expanding knowledge about energy storage, but at the state level, incorporating different market-pull mechanisms has become the norm. As an early mover in energy storage, California provides the richest history of policy development and the best benchmark against which to evaluate state-level policies in the US.

California's policy strategy has three main elements: (i) creating a demand for energy storage through utility-scale procurement targets, (ii) supporting investment through financial incentives, and (iii) providing funding for RD&D to drive technology costs down and demonstrate the value of EST in real-life applications. Other market-pull instruments, such as the ESR and renewable mandates, have also helped to accelerate investments and create legitimacy for energy storage. As shown in Fig. 7, storage in California has not grown uniformly, and policies have been added or adjusted in a sort of 'learning-by-doing' process. However, as a whole, California's policy strategy has positioned the state as the most mature energy storage market in the US [65] and, today, California has the largest amount of storage projects in operation and the largest battery storage capacity in the country [17].

Massachusetts and New York have mirrored California's strategy, albeit with a few differences. For example, while California's rebates and New York's bridge incentives support several technologies, Massachusetts' SMART programme is directed exclusively at solar-plus-storage projects. Another difference is that New York has introduced other elements, such as loans and expert-driven assistance services. Policy efforts in Massachusetts and New York are still relatively recent, so their impact on storage deployment is yet to be determined.

Germany has prioritised technology-push policies, specially RD&D funding for electrochemical and hydrogen storage projects. It has not adopted procurement targets, and financing opportunities are limited to specific applications, particularly solar-plus-storage and heat storage systems. This policy portfolio and the relatively slow growth of storage capacity suggest that deploying energy storage is not seen as a short-term priority in Germany. Rather, there is a general understanding that VRE can continue to expand without new storage additions in the next few years [56]. However, the phase-out of nuclear and coal power plants, the congestion issues caused by the imbalance of wind capacity between northern and southern Germany, as well as the public opposition to grid expansion projects [37], might lead policymakers to view energy storage as a more pressing issue in the near future.

6.2. Policy recommendations for Mexico

The priority for Mexico should be creating a legal definition of energy storage and designing clear regulations for the operation of EST in the WEM. In Mexico, defining energy storage as a generation or a transmission and distribution asset is not only critical to establish revenue streams, but also to determine whether EST will be able to operate under a regime of free competition. Because private and public actors have different abilities to mobilise and allocate resources [104], future regulations regarding the legal role of energy storage could significantly impact the speed and efficiency with which energy storage is deployed in the country. Some authors advice against defining energy storage under any traditional categories and advocate for the creation of a new asset class for energy storage [13,19]. However, since the electricity supply chain is defined by the Mexican Constitution, creating a new asset class for energy storage might require a constitutional reform [19].

Based on FERC's Order 841 [42] and common recommendations in the literature [11,12], Mexican policymakers should consider at least the following measures when designing market rules for energy storage: allowing EST to offer multiple services in the WEM, even simultaneously; creating new markets for services that are currently not available in the WEM; adjusting bidding parameters to account for the special operational features of EST (e.g. faster response times, charging limits); removing technical requirements that might prevent EST from participating in the market (e.g. minimum size requirements); and revising pricing methodologies to ensure EST are fairly remunerated.

Both the Transition Strategy to Promote the Use of Cleaner Technologies and Fuels [22] and SENER's working group on energy storage [59] suggest that RD&D should be a priority for Mexico. Although RD&D has indeed been a crucial policy in the US and Germany, Mexico's annual RD&D budgets are significantly lower. In 2018, Mexico spent only $0.4 billion in energy-related RD&D, while Germany and the US spent $1 billion and $7 billion, respectively [105]. Mexico should take advantage of its position as a late mover and direct its limited funds towards demonstration projects of technologies that have already been proven to be effective in other countries, and evaluate how they could fit within the Mexican grid. Mexico could benefit from the knowledge and cost reductions that have resulted from innovations in other countries and select projects with less technological uncertainty. Mexican policymakers should also pursue building public-private partnerships and international collaborations to fund these projects.

To accelerate investments and promote the formation of a storage market, Mexico should introduce technology-push and market-pull policies simultaneously. Procurement targets could be used if policy-makers decided that energy storage is a short-term priority, as in the case of the US. This could occur if Mexico's energy transition goals or other international commitments increased in ambition in the following years, or if other inexpensive flexibility options became limited. Otherwise, rebates, loans, investment grants, tax credits and other financial incentives could be enough to build a market, as in the case of Germany. These financial incentives could be "neutral" and support several EST or they could target specific technologies, such as solar-plus-storage projects. Further studies about technology costs, site availability (for example, hydropower facilities for PHS or caverns for CAES), and the necessities of the Mexican grid could help identify whether certain technologies should be specifically targeted by incentives in the future.

6.3. Limitations

This analysis has three main limitations. First, it studies regulations and policies qualitatively, but it does not evaluate the quality, intensity, complexity or degree of implementation of these interventions. Second, it does not establish any strict evidence of causality between specific policies and the rate of energy storage deployment in a jurisdiction. Quantifying the impact of each individual policy on the development of energy storage capacity was beyond the scope of this paper. Finally, there are more institutional, technological and social differences between the analysed jurisdictions than those discussed here, as well as other external factors, such as international and regional trends, that could affect the development of energy storage.

7. Conclusions

The comparative policy analysis in this paper has shown that energy storage has usually been incorporated into policy agendas as consequence of broader energy transition plans that feature a significant increase in VRE. The analysis has also confirmed that the deployment of energy storage depends on the existence of supportive regulations and policies that allow EST to make a profit in the market.

The main priority for policymakers in Mexico should be providing a legal definition of energy storage and designing a clear regulatory framework for the operation of EST in the WEM. As a late mover, Mexico could benefit from the knowledge and innovations developed in other countries, and direct its limited RD&D budget to projects with less technological uncertainty and focus on demonstration projects that display how energy storage could operate under the specific conditions of the Mexican grid. If energy storage deployment is considered a priority in the following years, Mexico could accelerate investments through a mix of storage procurement targets and financial incentives. A strong storage market can also be built over time by offering rebates, loans, investment grants, tax credits or other financial incentives.

Future research can be directed at studying the conditions and necessities of the Mexican grid to identify which EST could be a best fit for Mexico and how policies could be adapted to support those specific technologies in the future.

CRediT authorship contribution statement

C.V. Diezmartínez: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The author would like to thank Dr. Pablo Salas for his invaluable guidance in the creation and development of this project. This work would not have been possible without his support. The author is also grateful to Professor Laura Diaz Anadon for her thoughtful comments and suggestions since the beginning of this project. Finally, the author is grateful to the three anonymous reviewers that helped improve this work with their highly constructive feedback.

This work was supported by a joint scholarship from the National Council of Science and Technology (CONACYT) and the Innovation and Technology Transfer Institute (I2T2) of the state of Nuevo Leon, Mexico.

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